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PROPORTIONAL HYDRAULIC VALVE CONDITION MONITORING METHOD FOR ON-LINE FAULT DETECTION

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Abstract: *This paper presents the development of a method for condition monitoring and on-line fault detection on proportional directional valves used on the speed governor of hydroelectric power plants. The method is based on monitoring both the valve supply current and spool position related to a control signal for the valve spool positioning which takes into account the dynamic behaviour of friction and flow forces, solenoid current and valve closed loop controller. For valuation and validation of the method, experimental results with the valve under healthy conditions and with induced faults were compared. Faults were added in a way to represent spool locking and increase of friction forces between the spool and sleeve. Considering that the proposed method requires reference parameters characterizing the valve operation without fault, standard performance tests were proposed to determine the initial parameters. The obtained results prove the effectiveness and robustness of the method for the detection of faults classified as severe even if the valve controller attempts to compensate any faulty behaviour. The method is capable to detect the evolution of the described faults and, based on specified set points, to provide alarms for maintenance.*

Keywords: *Proportional valve, condition monitoring, fault detection*

1. INTRODUCTION

On electric energy generation systems, the control of power and frequency of the generated energy is fundamental to keep grid stability, power supply and safety of system, workers, users and equipment connected to it. On hydroelectric power plants, regulation of speed/power is made through the control of the turbine wicket gate position by a hydraulic actuation system normally composed by power unit, proportional directional valve and cylinder.

In the hydraulic systems of speed governors of Kaplan and Pelton turbines , the proportional directional valve lies in series with the other components from the point of view of reliability, as presented by Vinadé et al. (2002),. This means that a fault in this component leads to a failure of the entire system.

Common faults on proportional directional valves that affect their behaviour are spool lock, friction increase, loss of supply current or control signal, excessive wear, break of internal component and solenoid heat up or burned coil. Those faults are mainly caused by contaminated fluid, manufacturing deviation and high current or voltage supply. They can be detected by monitoring the fluid contamination level, solenoid temperature, spool position and solenoid current. The last two are commonly used by fault detection and diagnosis methods to evaluate the valve behaviour, as presented in Siivonen et al. (2007).

The outcomes of these faults can be detected by a deficiency in spool positioning control and an abnormal behaviour of the supply current. The method presented in this paper was developed to detect faults by comparing both the spool position and the supply current with theoretical limits of valve behaviour estimated by an algorithm based on healthy valve parameters. Considering the classification of condition monitoring methods presented by Hindman et al. (2002)), the proposed method belongs to the class of parameters and state estimation methods, where the parameter is tracked over time and significant deviations from a specified threshold indicate a fault.

A set of three different cylinders and four different proportional valves were used for validation. Tests with three different supply pressures that represent the usual working pressure for this kind of application were carried out for each combination of valve and cylinder aiming to evaluate the capability of the fault detection method to work with different configurations of hydraulic systems.

The internal closed-loop controller of proportional valves acts in a way to correct the position errors even when in faulty operation. Because of that, certain faults will not be able to overcome the valve controller and they are not detected through the spool position monitor. It was observed that in most of those cases the valve requires an abnormal level of electric current to achieve the desired spool position. By monitoring the supply current it is possible to detect this kind of fault.

2. FAULT DETECTION METHOD

2.1 Test Setup

The test setup was constituted by a proportional valve and a cylinder aiming to reproduce common hydraulic systems that are applied on hydroelectric power plants (Figure 1). The procedure presented herein is based on previous research presented in Ramos Filho (2009) and Ramos Filho e De Negri (2013) where a model-based fault detection method for hydraulic servoproportional valves has proposed.

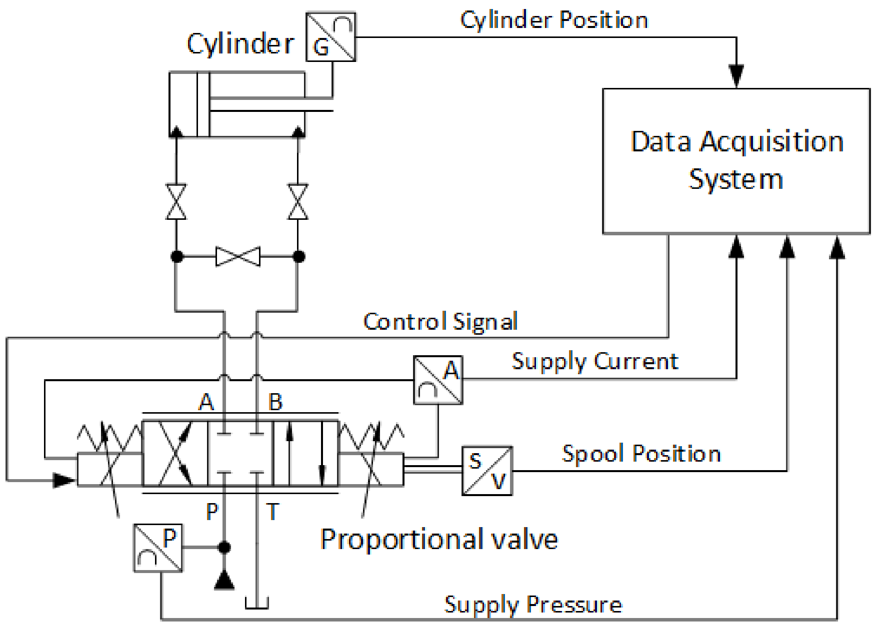

Figure 1. Hydraulic circuit of the test bench.

By receiving the control signal, the valve will provide the solenoids with a controlled supply current to move the spool to the desired position. Therefore, the spool position and supply current are functions of the control signal.

Aiming to determine the faulty behavior of the valve it is necessary to establish its healthy condition as a reference. In this way, it will be possible to compare the valve actual behavior with the one expected and consequently, to identify a faulty behavior. A set of experiments were carried out aiming to determine the reference parameters for a healthy valve. These parameters were acquired by applying a sinusoidal control signal with amplitude equal to the maximum spool displacement of the valve, which is a standard test, in order to capture the hysteresis and dynamic feedback from it.

2.2 Spool position

Figure 2. shows the spool position versus the control signal, as a result of the standard test mentioned above. The sinusoidal input signal had amplitude of 10 V and frequency of 0.5 Hz such that dynamic effects could be neglected.

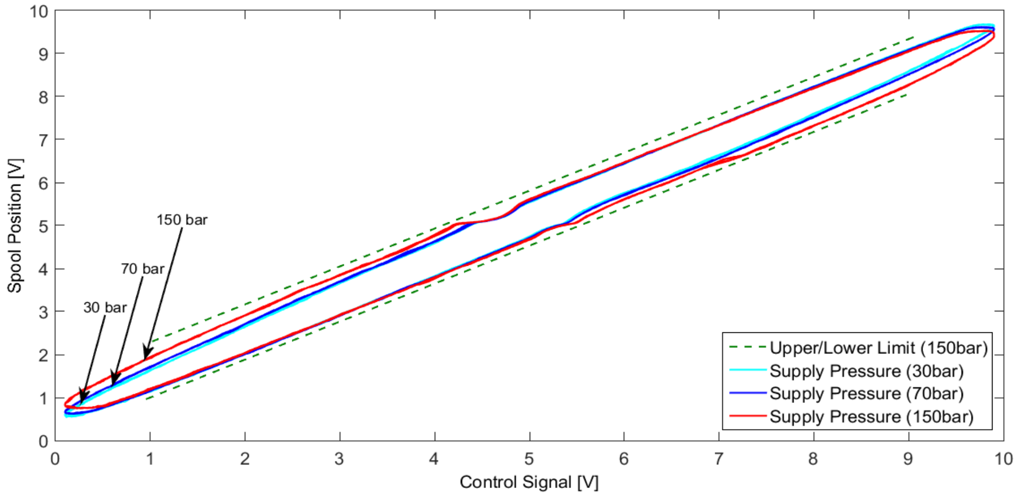

Figure 2. Spool position versus control signal for supply pressures of 30 bar, 70 bar, and 150 bar.

The valve hysteresis is a consequence of the solenoid electromagnetic effects and non-linear friction between spool and valve sleeve. The presence of spool positive overlapping on the null region, around 5 V, can be also observed in Figure *2*. The upper and lower sides of the curves in this figure were linearized and an offset (additional value in the linearized curves aiming to cover spool work range) was added to both equations. Therefore, two linear equations were obtained for each considered supply pressure.

Those sets of two equations define the new valve operating regions which is considered non-faulty. For a given control signal, the expected range for the spool position is calculated and if the spool signal gets outside this range, it is considered a faulty state. Even though the higher pressure is sufficient to describe the valve behavior for the lower pressures, a healthy operating region for each pressure was considered.

The fault detection depends on the values attributed for these offsets. The smaller the offset is, more sensitive the system can be. Considering this, it is necessary to evaluate the system requirements in order to set appropriated offset values.

2.3 Supply current

The method to be checking the supply current is similar to the spool position method. By measuring the supply current for each solenoid it was observed that the supply current of the whole valve is the sum of both solenoids currents despite the amplification that occurs inside of the valve electronics, as can be seen in Figure 3.

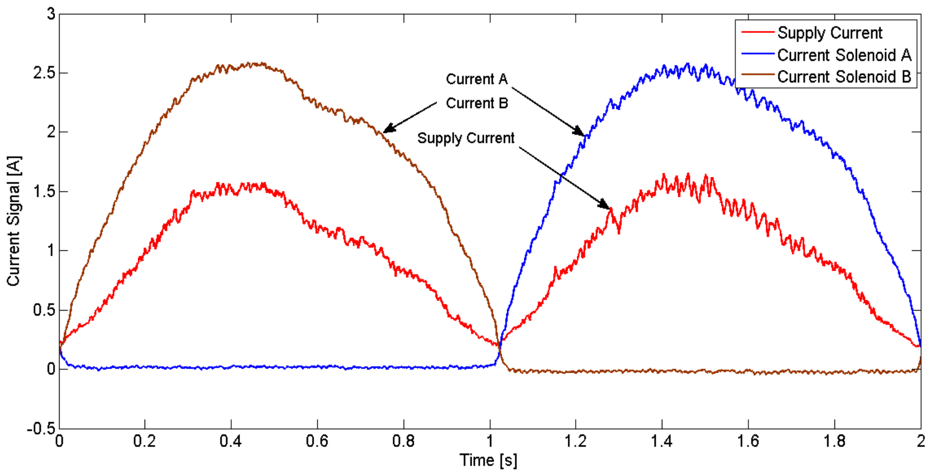

Figure 3 - Supply current and each solenoid current for a sinusoidal reference signal.

With this analysis, it is possible to observe that the supply current behavior is very similar to the current on each solenoid. Therefore, a fault detection method can be based on the supply current.

In order to set the healthy working region, the supply current is plotted against the control signal as shown in Figure 4.

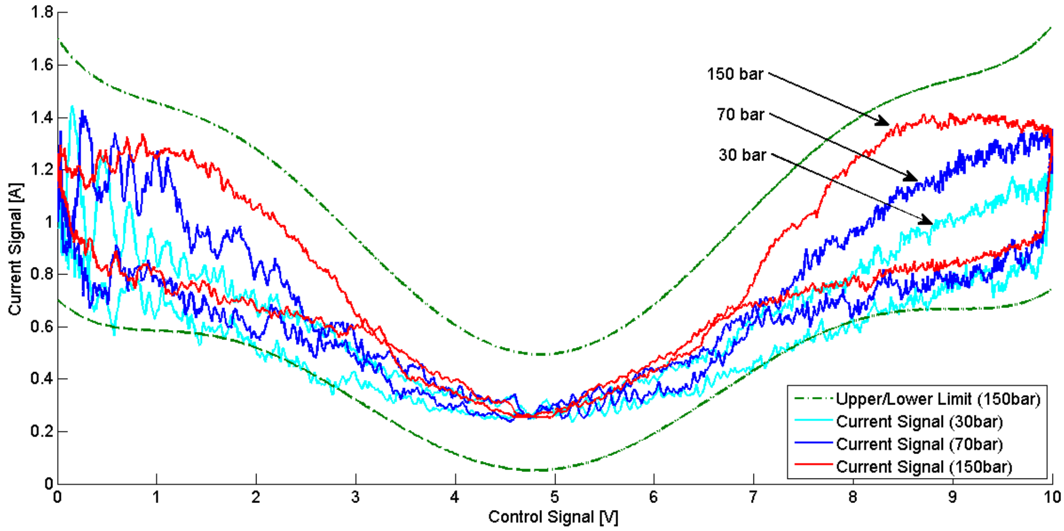

Figure 4 - Supply current versus spool position control signal.

Because of the complexity of curves shape, a polynomial regression was used to generate the upper and lower limits. An offset is applied to both curves to increase the range of the healthy operation region of valve. Differently from the spool position monitoring, the current behavior changes considerably with the supply pressure value. Consequently, they can not be approximated just by the higher pressure curve.

The limits determine the region where the valve supply current is considered normal. A fault is considered when the current value steps outside this region.

3. FAULT INDUCTION SYSTEM

To evaluate the fault detection method performance, a system for fault induction was developed based on Bhojkar (2004). The author developed a fault simulator and evaluated its capacity to induct faults over a proportional valve. It was used an extra solenoid to act against the valve spool movement. This actuation was carried out in a way to emulate different friction forces (static, Coulomb and viscous) between the spool and sleeve of the valve.

In this project, a proportional solenoid similar to the proportional valve solenoids to act as a fault inductor was used. The constructive characteristics of the tested valves allowed for the external coupling of the extra solenoid in a way that the valve does not suffered any damage, giving to the test a non-destructive characteristic.

The solenoid force was evaluated by a load cell for supply currents between 0 and 3 A and for five different solenoid core positions (1, 2, 3, 4, and 5 mm). The position 0 mm corresponds to the maximum displacement of the solenoid core in the direction of the valve spool and the 5 mm corresponds to the lower position, in the opposite direction of the valve. Based on that, it is possible to know, for a given current level, the force the solenoid is able to produce for different positions along its stroke.

Proportional solenoids are developed to keep a constant force through a certain part of its stroke for a given constant level of current. The results obtained showed that the solenoid proportional stroke is between the positions 1 to 4 mm where a low force variation is observed. Figure *5* shows the curves obtained in these tests.

The solenoid C (fault induction solenoid) was attached outside the valve. Its core was placed in contact with the valve safety pin, so that it could work by acting upon it. The distance between solenoid C and the valve was adjusted in a way to keep it inside its proportional stroke region, making the induced force to be constant over the spool displacement.

The entry signal of the fault simulator is the supplied current that comes from an external source and the output is the emulated force over the valve spool. By varying the intensity of the force is possible to know the sensibility of the fault detection system that is based on previously determined condition parameters.

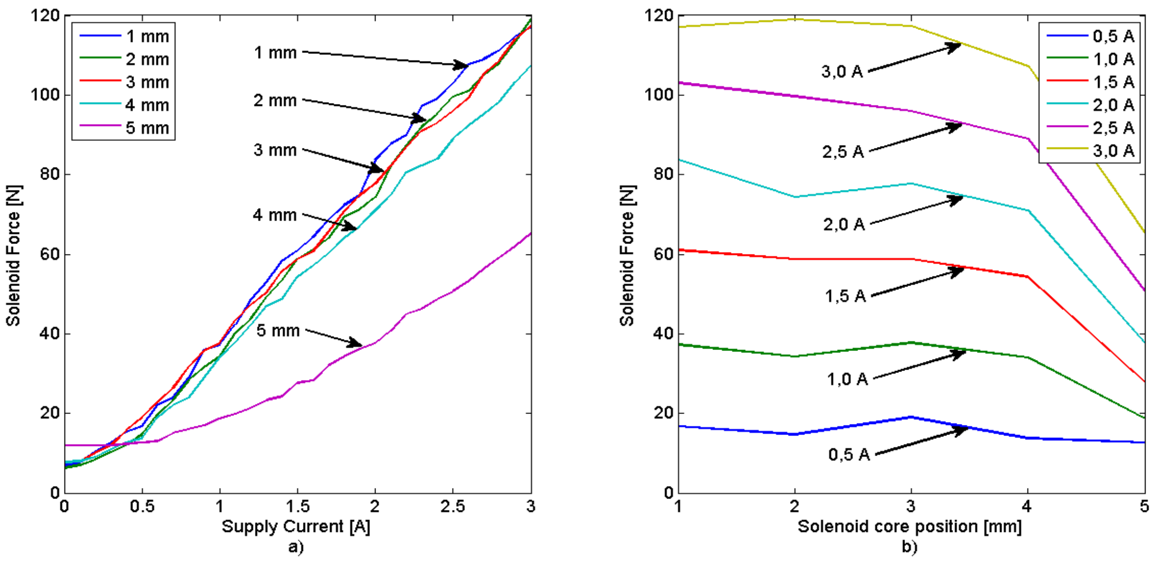

Figure 5. Fault induction solenoid tests: a) force versus supply current and b) solenoid force versus core position.

4. EVALUATION OF THE FAULT DETECTION SYSTEM

For the evaluation and validation of the method, experimental results with the valve under healthy conditions and with induced faults were compared. The healthy conditions were determined without the fault induction solenoid C attached to the valve.

The position is measured in Volts, where 0 V is when the spool is at maximum closing stroke of the valve and 10 V is when the spool is at maximum opening stroke. A set of tests were carried out with the valve not attached to a cylinder. The port A of the valve was directly connected to port B. The results are presented in sessions 4.1, 4.2 and 4.3.

Another set of tests with the valve attached to a cylinder were carried out. They are presented in sessions 4.4 and 4.5. The difference is that the valve control signal is now a result of the cylinder closed loop position control.

4.1 Spool locking without cylinder

A spool locking fault was induced to the valve by limiting the spool displacement. It was limited to the position corresponding to 8 V. Figure 6 shows the result of the test. It can be seen that the fault is detected when the spool position goes out of the limits.

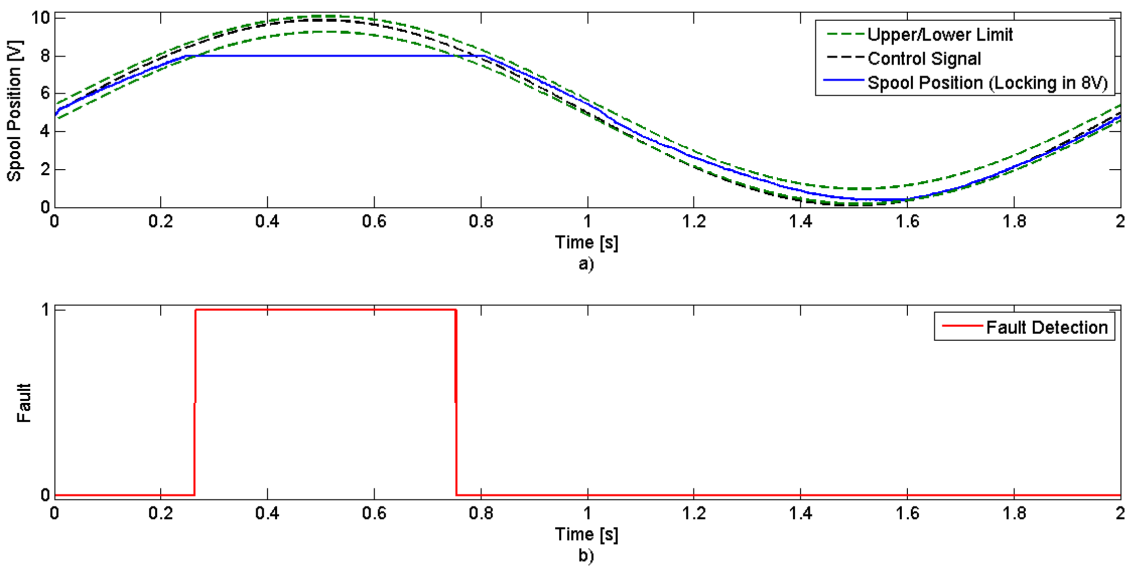

Figure 6. Result of fault detection in the valve spool locking test.

4.2 Sinusoidal control signal without cylinder

A sinusoidal control signal with 5 V of amplitude was applied to the valve covering the entire spool stroke. Figure 7 shows the results for this test. Figure 7 b), c) and d) are the measured supply current for different fault induction solenoid currents (0 A, 1 A and 2 A). It was noticed that even with these magnitudes of induced current, the valve was capable to guarantee the positioning of the spool, as shown in Fig. 7a.

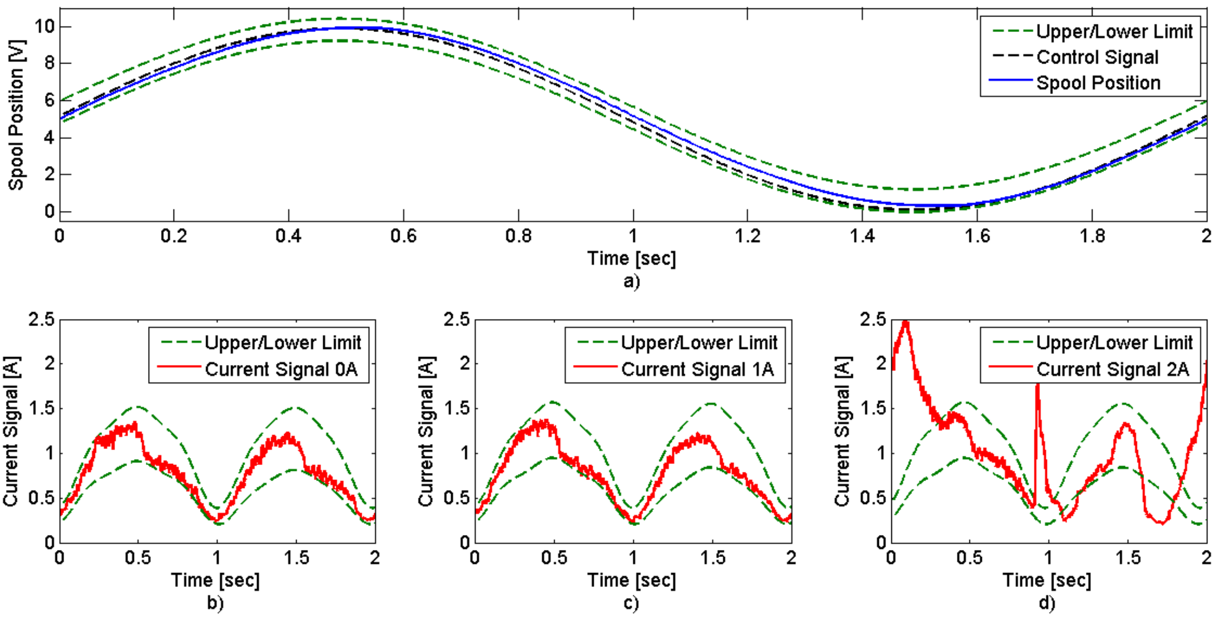

Figure 7. Measured current for a sinusoidal control signal and different fault induction currents.

4.3 Step control signal without cylinder

A sequence of step control signals were applied to the valve as shown in Figure 8 a). Figure 8 b), c) and d) are the measured supply current for different fault induction solenoid currents (0 A, 1 A and 2 A).

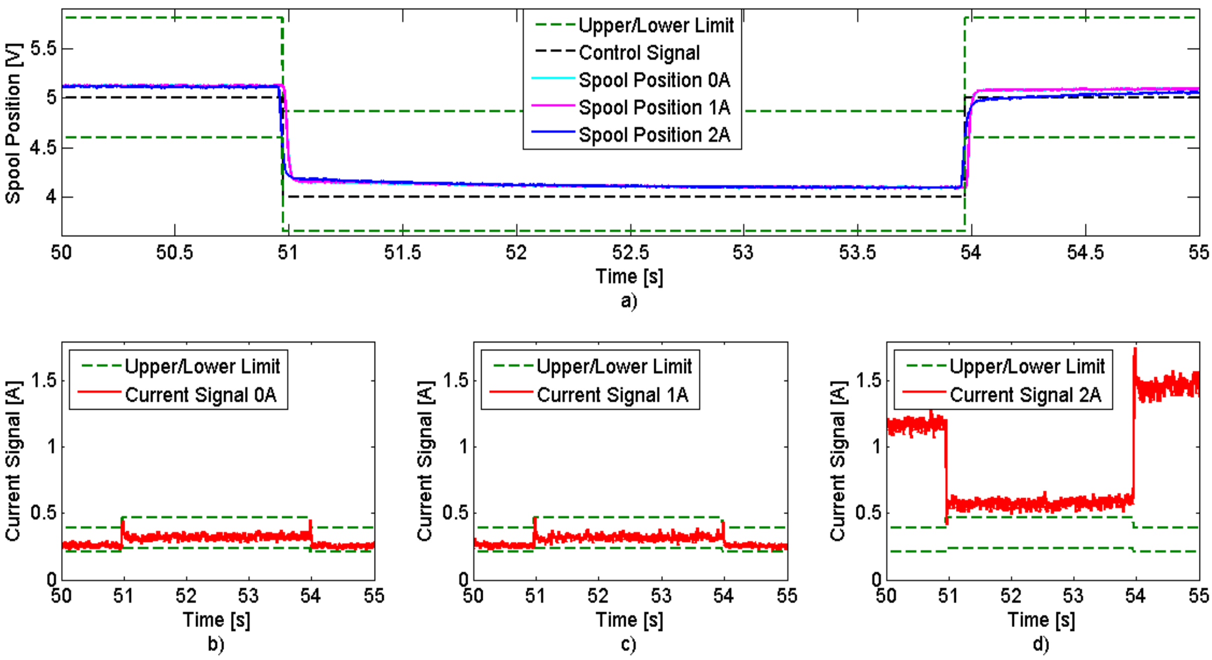

Figure 8. Results for the step control signal for three different fault induction currents.

4.4 Sinusoidal control signal with cylinder

The sinusoidal control signal was set to cover all cylinder stroke. For this test it was noticed that the spool position changes significantly from one fault induction current to the other ones. The results are presented in Figure 9. Figure 9 d), e) and f) are the measured supply current for different fault induction solenoid currents (0 A, 1 A and 2 A).

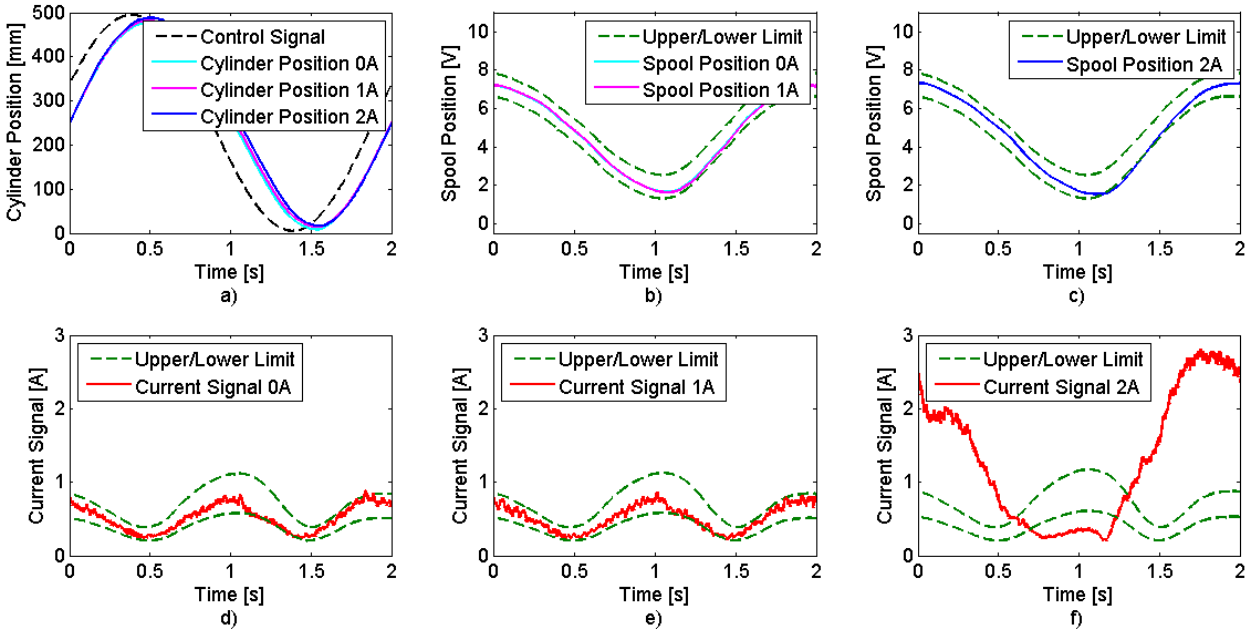

Figure 9. Results for fault induction over the valve with cylinder.

4.5 Step control signal with cylinder

Figure 10 shows the obtained results for a cylinder step control signal. Figure 10 c), d) and e) are the measured supply currents for different fault induction solenoid currents (0 A, 1 A and 2 A).

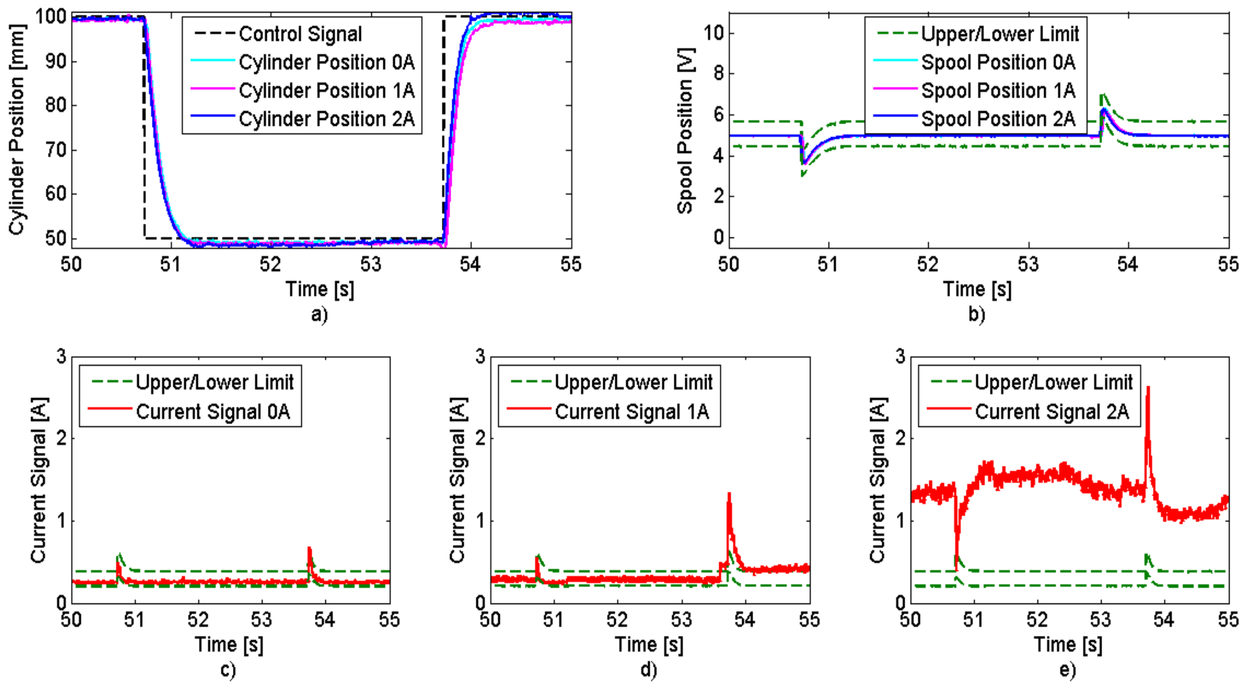

Figure 10. Results for the cylinder step control signal.

5. CONCLUSIONS

It was noticed that even with high induced forces over the spool (1 A = 35 N, 2 A = 80 N) the valve internal controller was capable to perform the spool positioning. The detection of faults by means of position monitoring becomes less sensitive because of the valve controller robustness. It was also noticed that the position fault detection method is capable of detecting spool position locks with high accuracy.

In most of the induced faults it was noticed that the valve supply current suffers a significant change in shape and magnitude. Since the fault detection method takes into account both shape and magnitude of the supply current it was capable of detecting most of the induced faults.

The described method is based on offsets that can be adjusted. This means that the limits of the healthy condition region can be tuned to make the fault detection more sensitive.

One positive point of this method is the small number of external transducers involved on it. Except for the supply current that requires a current transducer, all signals demanded by the fault detection method are provided by the valve input/output. In this way, no damage is done to the valve and its warranty and physical characteristics are maintained.

The application of fault detection and condition monitoring systems for proportional valves can be useful for predicting the time for maintenance and this can reduce costs and avoid hazardous system failures.

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